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Co-benefits of large scale plug-in hybrid electric vehicle and solar PV deployment

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HIGHLIGHTS

► Mid-day charging may be needed to maximize the all-electric performance of PHEVs.
► Mid-day charging adds to peak electric demand.
► Solar PV can reduce the net increase in demand created by PHEVs.
► PHEVs can absorb otherwise curtailed PV energy during periods of low demand.

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ABSTRACT

A number of studies have found that plug-in hybrid electric vehicles (PHEVs) will have relatively small grid impacts if charged with overnight off-peak electricity. However the greatest petroleum displacement will occur if vehicles are allowed to charge during the day, maximizing all-electric range. Charging during the day also allows for a smaller, lower cost battery. Mid-day charging will add to peak electricity demands and may occur in locations where it is difficult to construct new generation and transmission capacity. Solar photovoltaics (PV) provide an option to provide mid-day peaking capacity. Mid-day charging of PHEVs also may absorb low value or even curtailed PV generation during periods of low demand. This study identifies possible co-benefits of large scale PV and PHEV deployment by simulating the Texas grid and identifying changes in peak capacity requirements and PV curtailment. A modest deployment of PV is able to avoid most of the increase in capacity requirements associated with very large PHEV penetrations. PHEVs are also able to reduce curtailment at high PV penetration, especially if charging can be controlled to improve the coincidence of consumer charging demand with normal PV generation patterns.

1. Introduction

Plug-in hybrid electric vehicles (PHEVs) offer an option for partial electrification of the transportation sector and enable the use of low carbon or carbon free sources of electricity to displace petroleum use. PHEVs can also take advantage of low-cost off-peak electricity to reduce cost of vehicle charging. Previous studies have found that even large deployments of PHEVs are unlikely to burden electric power systems with additional capacity requirements if vehicle charging can be controlled and limited to overnight, off-peak charging [1–3].

Despite the low cost of overnight charging, using exclusively off-peak night-time electricity may limit the petroleum displacement and other benefits of PHEVs [1,4]. The high cost of PHEV batteries may limit the electric range of marketable PHEVs. Allowing a vehicle to recharge during the day could increase the fraction of vehicle miles traveled on electricity while reducing the size and cost of the vehicle battery. Overall, a PHEV with smart or controlled mid-day charging may provide overall improved economic performance to the vehicle owner (including long-term price stability of fuel) and greater environmental and national security benefits to society as a whole. Depending on vehicle charging patterns, mid-day charging may require increased capacity and generation during on-peak periods. This may also require new transmission and distribution capacity which can be difficult to construct, especially in urban load centers.

Solar photovoltaic (PV) electricity provides a potential source of mid-day charging of PHEVs which can be sited at the point of demand [5,6]. While PV is often considered a source of mid-day "peaking" energy during hot summer months, it also generates significant amounts of energy during times of lower peak demand

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in the non-summer seasons. Previous analysis has demonstrated that as PV penetration increases, the increasing difference between PV supply and normal demand patterns may lead to "surplus" PV generation [7]. This problem is exacerbated by the need to keep thermal generation online to provide additional operating reserves at high penetration of PV to address solar variability and uncertainty.

To avoid curtailment at very high levels of PV penetration, the flexibility of the grid will need to be increased, and some alternative uses of electricity generated in the middle of the day must be found. A variety of options will likely be necessary including load shifting, energy storage and increased electrification. Among the electrification options is mid-day charging of PHEVs. The ability of PHEVs to provide a controllable load can potential enable greater penetration of PV and provides another market for this renewable energy resource.

The potential co-benefits of PHEVs and PV deployed at a large scale are dependent on the supply characteristics of PV and the demand characteristics of normal electricity use and potential vehicle charging. In this work, we examine these potential co-benefits by simulating the performance of an electric power system with a large penetration of PV and a transportation system with a significant share (up to 50%) of PHEVs. We begin by reviewing the basic characteristics of PV generation in "conventional" electric power systems and illustrate the limits to PV deployment at high penetration. We then discuss the performance of a PHEV fleet under different charging profiles and driving patterns. Finally, we provide an analysis of the co-benefits of PV and PHEVs when deployed on a large scale, demonstrating the improved performance of PHEVs when allowed to charge from mid-day PV generation and the increased penetration of PV allowed by PHEV deployment.

2. The limits of PV deployment in conventional electric power systems and the potential role of PHEVs

There are several inherent limits in the ability of solar PV to supply a systems' electricity without "enabling" technologies such as energy storage. Most obviously, solar PV cannot supply night-time electric demand. However, the supply characteristics of PV could limit its contribution during the day. The limits of PV to meet an aggregated load at the system level have been demonstrated previously [7,8]. The basic conclusion of this previous work is that the narrow window of PV output can produce unusable generation during the middle of the day, especially during non-summer months. A large fraction of PV electricity generation occurs during periods of moderate demand and this PV output can exceed actual demand, especially considering the limits of "baseload" power plants to decrease output during the short window of high solar output.

Fig. 1 illustrates the challenges faced in deploying large amounts of PV energy. In this figure, we have simulated a large amount of PV in the Electricity Reliability Council of Texas (ERCOT) grid producing enough energy to provide 15% of the system's annual electricity in the year 2005. The simulations use the REFlex model [9], discussed in more detail in Section 4. The graph shows the normal electric demand, the PV generation, and the resulting net load, which would have to be met by conventional generators during a 4-day period from April 25 to April 28.

During these four days, moderate temperatures reduce total electricity demand for heating or cooling (compared to the peak demand of about 60 GW in the summer and about 41 GW in the winter). During the middle of these four days, the combination of relatively high solar output and low demand results in PV meeting a large fraction of the total electricity demand. This results in

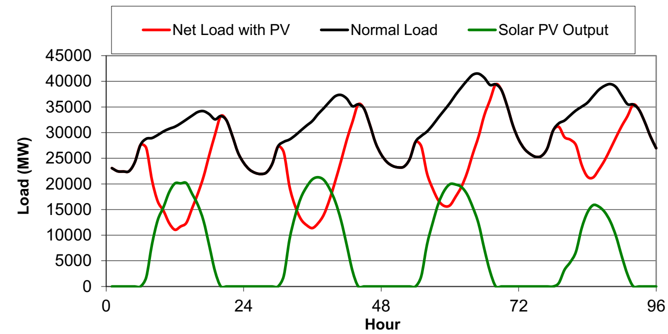

Fig. 1. Coincidence of PV and load during April 25–28, 2005 in ERCOT.

a second, more extreme off-peak period during the middle of the day, compared to the normal off-peak period in the early morning hours. Depending on the mix of generators meeting the residual load, the system may be unable to ramp at the rate, and over the range required by the use of this level of variable generation [10]. Limits to the grid flexibility include the ability of baseload units to vary output and the need to keep thermal units online to provide operating reserves.

The combination of constraints on system flexibility, and the limited coincidence of solar PV supply with normal demand patterns will result in curtailed PV generation at high penetration. The level of PV penetration illustrated in Fig. 1 may not be achievable without curtailing some mid-day generation, depending on the flexibility of the generator mix and reliability requirements. Estimating the overall flexibility of a power system, including its ability to ramp, reduce load, and provide operating reserves is difficult, and will likely change over time as new generator types are introduced, especially over the time scales needed to introduce large amounts of both PV and PHEVs. However, a simple flexibility metric can be used to determine the relationship between conventional generation operation, PV penetration and curtailment. Fig. 2 illustrates the curtailment that results at increasing penetration of PV in the ERCOT grid in a scenario where the system is able to accommodate PV over a cycling range of 80% of the annual demand range [7]. This corresponds to a "flexibility factor" of 80%, meaning the aggregated generator fleet can reduce output to 20% of the annual peak demand [9]. Both the average and marginal curtailment rates are shown. The average curve shows the total curtailment of all PV at a certain generation level. At the overall assumed system flexibility level, by the time PV is providing 20% of total demand, about 7% of all potential PV generation is curtailed. The figure also shows the marginal curtailment rate, or the curtailment rate of the incremental unit of PV installed to meet

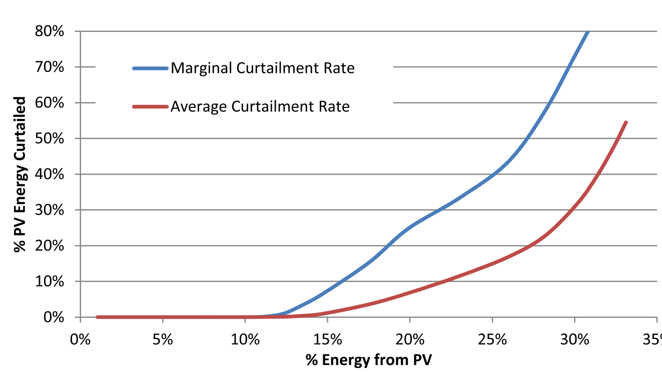

Fig. 2. Curtailment as a function of PV energy penetration assuming an 80% system flexibility.

a given level of PV penetration. If curtailment were assigned on an incremental basis, at the point where PV is providing 20% of total demand, about 25% of this incremental PV generation would be curtailed.

This curtailed PV will result in an increase in levelized generation costs for solar, since it will be able to sell less energy (decreased capacity factor) and must recover costs over the reduced amount of energy actually sold.

If PV is to provide a large fraction of a system's electricity, some valuable use must be found for excess mid-day PV energy. Overall, this requires increasing the flexibility of the electric power system, which could include demand response, load shifting, more flexible generation, sharing load and energy supply over larger geographical regions (taking advantage of increased spatial diversity), and energy storage [11].

While it is likely that all of these options will play an important role in the integration of PV, an additional option is creating new, dispatchable demands for electricity. This demand must be flexible in when it must charge. PHEVs provide a unique source of additional load, since it has the potential to be controllable – able to be dispatched by a utility or system operator, with flexibility in the exact time of charging, and not depend on specific season or weather conditions. PHEVs also do not represent critical loads – on occasions where demand for electricity is extremely high and therefore very expensive, charging can be deferred to a later time. As a result, PHEVs have been proposed as a source of controllable load to absorb potentially excess generation from variable renewable sources [12].

3. PHEV overview and advantages of mid-day charging

PHEVs are similar to conventional hybrid electric vehicles, but feature a larger battery and plug-in charger that allows electricity from the grid to replace a portion of the petroleum-fueled drive energy. PHEVs reduce petroleum use and produce lower tailpipe emissions when operating electrically, but without the range restrictions of pure battery electric vehicles. They also increase diversification and price stability of fuels, since electricity can be generated from many different primary fuel sources.

There has been considerable analysis on the technical and economic performance of PHEVs [13–17]. Among the notable conclusions are that the economics and consumer acceptability of PHEVs are limited by the high "first costs" associated with the battery [18–21]. In the United States, the PHEV electric performance is often designated by the nomenclature of "PHEV-XX", with the XX representing the vehicle's approximate battery storage capacity in miles, such as PHEV-20. It should be noted that a PHEV-20 will not necessarily be able to travel 20 miles on pure electric drive – an "optimized" power train configuration may require blended mode (electric and IC engine) travel at high speeds, during heavy acceleration, or traveling at grade.

The lowest cost and lowest impact charging of PHEVs would generally use controlled charging to maximize use of off-peak electricity [1–4]. Alternatively, the role of PHEVs to absorb off-peak wind energy (largely during overnight hours) has also been considered [22–24]. While the "single overnight charge" scenario allows the lowest cost electricity for PHEVs, this assumption is not necessarily the most economic. While mid-day electricity is more expensive than off-peak electricity, it is still far less expensive than gasoline [4]. The possibility of mid-day charging provides several addition options to increase the economic viability of PHEVs. Mid-day charging increases the fraction of miles driven electrically. An owner of a PHEV-20 with a 25-mile round-trip commute would be unable to drive completely on electricity with a single overnight charge. However, with some mid-day charging, the consumer could "top off" the battery during the day, enabling completely electric drive (assuming limited "blended mode" driving). One previous analysis of mid-day charging found that under ideal circumstances, mid-day charging decreased gasoline use by 39% compared to a single overnight charging scenario [4]. This reduced fuel use will results in substantially lower operating cost.

An effect of increased number of electrified miles due to mid-day charging is also the ability to downsize the vehicle battery. Downsizing from a PHEV-40 to a PHEV-20 would decrease the initial cost of the, and mid-day charging may enable the consumer to reduce the battery size while often achieving similar gasoline savings as a vehicle with a larger battery and only overnight charging [4]. (Downsizing the battery would also reduce vehicle weight and provide a small increase in efficiency.) This option allows a consumer to pay significantly less for the vehicle, which may be important for consumers that are very sensitive to "first costs" or with very high personal discount rates. The option of mid-day charging almost certainly makes PHEVs more attractive to consumers.

Challenges posed by mid-day charging include infrastructure availability and the impact of PHEV charging demands on utility loads, particularly in the summer months. PHEVs parked in city centers increase loading on potentially constrained transmission and distribution systems [25,26], especially since generation is generally located outside urban areas. For PHEVs to fully take advantage of mid-day charging, some supplemental mid-day generation, ideally located near or in urban centers is desirable. Solar PV is one candidate to provide some of this mid-day charging, especially since PV can be located close to load, minimizing the need for transmission infrastructure, as well as T&D losses.

As previously discussed, the supply of mid-day PV is uncertain, and any device designed to take advantage of this variable resource will ideally have a set of unique characteristics, primarily involving controllability and flexibility. PHEVs with the appropriate controls for "optimized" off-peak charging could use these controls to optimally use "on-peak" PV charging. Vehicles also may be somewhat flexible in when and how they absorb PV generated electricity.

Despite the flexibility of PHEVs, it cannot be automatically assumed that they will have battery capacity available during periods of surplus PV generation. Actual PHEV driving patterns must be compared to PV output to assess the actual coincidence of PV supply and PHEV charging demand.

4. Co-benefits analysis

The focus of this work is to consider large scale deployment of both PHEVs and solar PV, and considering the ability of these two technologies in combination to reduce overall vehicle petroleum use, electricity related fossil fuel consumption, and to mitigate negative grid impacts from either technology deployed in isolation. To evaluate these potential co-benefits, we ran a series of simulations of PHEV fleets, along with utility systems with both PV generation and PHEV charging.

4.1. Study location

The study location for this analysis is the Electric Reliability Council of Texas (ERCOT), which serves about 23 million individuals and represents about 85% of Texas's electric demand as of January 2012 [27]. Its electricity demand in 2011 was about 335 TWh, with a peak demand of about 68 GW. ERCOT is the smallest of the three U.S interconnects and is largely electrically isolated from the rest of North America, with limited transfer capacity with the rest of U.S. and Mexico. Texas has sufficient wind and solar resources to meet its entire demand, and has been a leader in wind deployment in the U.S. with over 9 GW installed by the end of 2011 [27].

4.2. Vehicle assumptions and analysis

We began by simulating the performance of two vehicle classes – a mid-size sedan and light-duty truck/sport utility vehicle. The vehicle design characteristics and performance were generated using the ADvanced VehIcle SimulatOR (ADVISOR) tool [28]. ADVISOR is an open-source vehicle simulation tool that models performance and fuel economy of vehicles based on real-world drive cycles [29]. Additional vehicle characteristics are provided in Table 1. The primary goal of these simulations was to determine the hourly electricity use of various PHEV types under different charging strategies. The ability to use PV as a charging source depends heavily on the vehicle driving patterns and hourly electricity use. The performance of the vehicle fleet for this study is based on actual driving-pattern data from Austin and San Antonio, Texas as part of the Texas Department of Transportation's 2007 survey. Seven hundred and eighty three days of drive cycle data (783 vehicles, each tracked one weekday) were collected over a period of 3 months in 2007. Vehicles were tracked with global positioning systems (GPS) to record the routes traveled and calculate their respective distances. The 1-second GPS data and vehicle simulations provide a temporal estimate of distance miles traveled, and determine when vehicles are parked [30]. The average daily driving distance for the 783-day set is 37 miles, with a median of 29 miles. This is similar to previous state-level estimates of travel for light-duty vehicles of 42 miles per day on average [31]. This data also indicates that the average vehicle is parked about 95% of the time. Fig. 3 illustrates the average distanced traveled in each hour for the analyzed data.

In addition to the PHEV-20, both vehicle types were also modeled as a PHEV-40, with a battery about twice the size as the PHEV-20 (14.1 kWh for the sedan and 18.8 kWh for the SUV). The added battery weight also produced a slight decrease in effective fuel economy.

In addition to these parameters, PHEVs are assumed to have a maximum battery depth of discharge of 65%, with a charging efficiency of 90% and a power electronics efficiency of 90%. The average charging rate was assumed to be 4 kW, based on an approximately 2:1 ratio of 120 V 20 A household circuits and 240 V 40 A heavy appliance/dedicated charging circuits rated at 85% for continuous service. The assumed mix of vehicles (cars to light trucks/SUVs) was assumed to be 1.1:1, based on the historical mix of light-duty vehicles in Texas [32]. As a result, the average vehicle will consume about 12.8 kWh per day. This assumes a wide offering of PHEV types in the future, including SUVs, light trucks, and other vehicles not currently offered.

4.3. Electric system simulations

Potential mid-day charging in ERCOT was combined with simulations of the ERCOT power system with PV generation. Grid simulations used the REFlex model, which is a reduced-form dispatch model used to assess the hourly coincidence of electricity supply and demand, considering the flexibility constraints of conventional generators [9]. REFlex can also be used to evaluate the impact of different forms of electricity storage and load shifting to increase the use of PV and other variable renewable generation sources [11,33].

Table 1
Modeled vehicle performance characteristics.

	Units	Sedan PHEV-20	SUV PHEV-20
Electric drive consumption (charge depleting mode)	kWh km^{-1}	0.19	0.25
Electric drive consumption (CD mode)	kWh mi^{-1}	0.30	0.40
Generator mode consumption (charge sustaining mode)	L/100 km	5.9	11.8
Generator mode consumption (CS mode)	Mpg	40	28
Battery energy	kWh	7.1	9.4

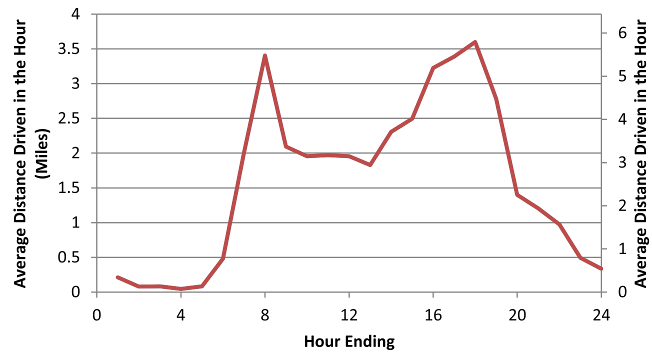

Fig. 3. Assumed average hourly distance traveled by light-duty vehicles in Texas.

We began with the base hourly electric demand for the ERCOT grid in the years 2005–2006. To this base demand, we added the simulated demand impacts of various penetrations of both PV generation and PHEVs. To estimate the impacts of a spatially diverse PV system, simulations were performed for several locations in each state with each site having multiple system types and orientations.

Solar data for 2005 and 2006 was derived from the updated National Solar Radiation Database (NSRDB) [34]. Solar insolation and temperature data was converted into hourly PV output using the Solar Advisor Model (SAM) [35]. A total of 49 sites in ERCOT were used for the simulation, with a mix of rooftop and utility-scale systems. The distribution of orientation was based on an assumed mix of 50% central and 50% rooftop. Of the central PV, it was assumed that 25% is fixed (south facing, tilted at 25°), with the remainder 1-axis tracking. The rooftop systems are assumed to be a mix of flat and fixed tilt systems with a variety of orientations. Additional details of locations and PV modeling assumptions are provided in [9].

REFlex scales the output from the simulated PV system to various sizes to examine the coincidence of PV generation with load, and examine grid impacts including changes in demand patterns and PV curtailment. Various penetrations of PHEVs were then added to examine how mid-day charging changes these various grid impacts.

The charging patterns are based on the vehicle simulations described in Section 4.1. The vehicle simulations provide a time series of the battery state of charge and when it is parked with the engine off and available for charging. Fig. 4 provides the average vehicle charging pattern for two vehicle types assuming it charges

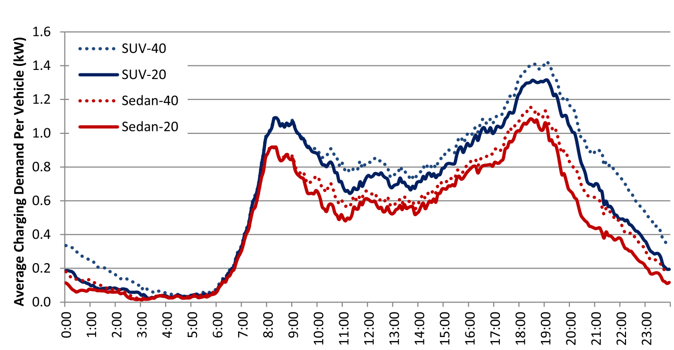

Fig. 4. Vehicle charging patterns assuming uncontrolled charging.

whenever the vehicle is parked. The data is shown at 5-min intervals. This "opportunity" charging case can form the basis for different assumptions regarding timing of charging and availability of charging stations.

The charging of individual vehicles was aggregated to the system level. Fig. 4 demonstrates that the uncontrolled charging demand is at its maximum immediately following the morning and evening commute. We discuss the impact of this charging pattern on normal electricity demand patterns, and the impact of varying this pattern in Section 5.

5. Results

The data produced by the ADVISOR and REFlex models produce a number of metrics to determine the co-benefits of PV and PHEVs.

5.1. Benefit of mid-day charging to PHEVs

We first examined the general benefits of mid-day charging to PHEVs, including increased electrification and potential decrease in battery size. Allowing vehicles to charge during mid-day periods increases the fraction of miles driven electrically, and decreases petroleum use, as illustrated in Table 2.

Table 2 demonstrates the significant advantage of allowing mid-day charging. A PHEV-20 fleet with mid-day charging shows a slightly greater petroleum displacement than a PHEV-40 with overnight charging. The increase in electric travel will reduce the life-cycle costs to the owner, and potentially increase adoption (this ignores variation in battery life differences between the vehicle types) [20]. However, it is important to consider the impact of mid-day charging on utility generation, transmission and distribution systems, and we consider various penetrations of a PHEV-20 fleet to examine these impacts.

5.2. Utility system benefits

The co-benefits of PHEV and PV charging can be described in two general categories – first PV mitigates the additional capacity required in the summer for mid-day charging and second PHEVs absorb potentially low value (or even unusable) PV energy during periods of low demand in the spring.

The first issue is illustrated in Figs. 5 and 6. Fig. 5 shows the normal electricity demand pattern in the ERCOT system for 4 days in the summer, along with the PHEV charging demand and the net demand. The PHEV penetration is equal to 30% of all vehicles, and the charging is assumed to occur in an uncontrolled manner – vehicles are assumed to begin charging at the end of each trip, assuming widely available charging stations. There are two noticeable impacts on the system load patterns from PHEVs: first, the total capacity requirements increase, and also, the system ramp rates increase, especially in the late morning. Additional capacity requirements may be difficult to meet, especially if PHEV charging is concentrated in urban centers which are traditionally constrained in both transmission capacity and the ability to build additional generation.

Table 2
Fraction of miles driven electrically and petroleum use.

PHEV type	% of Miles traveled electrically		% Petroleum displacement (compared to conventional vehicle)	
	Overnight charging only 10 pm–6 am	Opportunity charging	Overnight charging only 10 pm–6 am	Opportunity charging
PHEV-20	66.8	83.7	75.1	87.7
PHEV-40	82.9	93.6	87.1	95.1

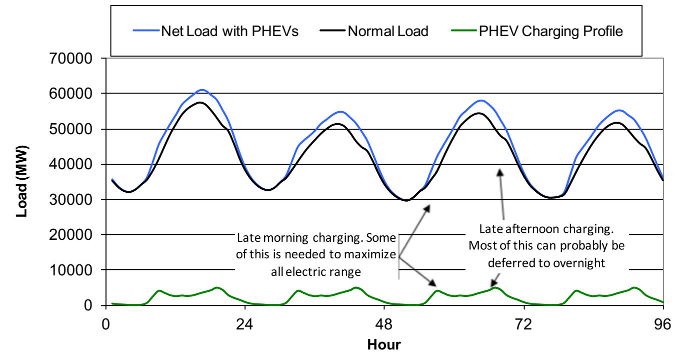

Fig. 5. Increased electric demand due to mid-day PHEV charging during July 5–8, with a PHEV-20 penetration of 30%.

Smart or controlled charging can potentially mitigate some of these impacts. As indicated in Fig. 4, the charging pattern includes a peak in demand following both the morning and evening commutes. The evening commute period is roughly correlated to the normal peak demand for electricity, and charging in the late afternoon will increase overall system demand. Most of the energy stored in the late afternoon or early evening will not be used until the following day. Therefore this charging can be deferred to the off-peak period in the early morning.

Fig. 6 illustrates the impact of controlled charging, where no charging is allowed between 3 pm and 9 pm. After 9 pm vehicles are charged in a quasi-optimal manner to uniformly fill the off-peak demand, with the requirement that the vehicles be fully charged by 7 am.

Deferring charging that would normally take place after 3 pm reduces the amount of energy needed during the peak period and the length of the peak demand, but does not decrease the actual peak demand. Alternatively, restricting charging an hour or two earlier can reduce the peak demand, however this begins to reduce the benefits of mid-day charging to the vehicle fleet. It also cannot address the fact that PHEV demand adds to the morning demand ramp rate.

PV generation can mitigate these impacts. Fig. 7 adds PV generation to the load shapes previously demonstrated. In this scenario PV system is large enough to provide 15% of the region's annual electricity demand. Controlled charging still occurs to shift late afternoon charging demand to overnight hours. However, this simulation does not assume any controlled charging in the day. It relies on the inherent correlation of PV and PHEV demand pattern. Since PV ramps up in a pattern similar to PHEV demand, the increase in net

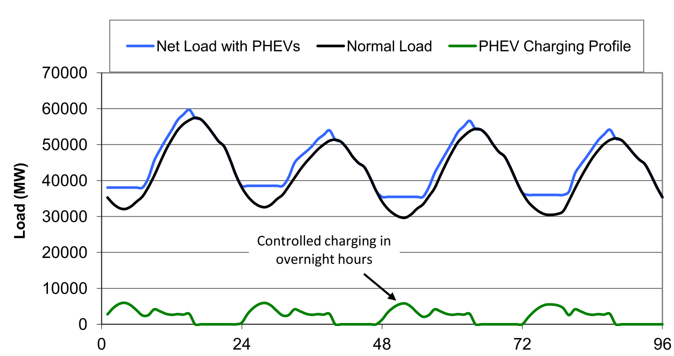

Fig. 6. Potential use of controlled charging to shift afternoon charging into overnight hours.

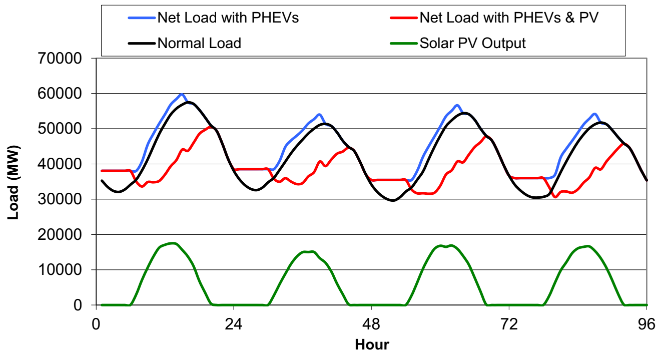

Fig. 7. Reduction in peak electric demand due to the deployment of PV providing 15% of the system's annual demand.

system demand is the same or less than the original (no PHEVs or PV) demand profile. PV has also met the increase in generation capacity needed by PHEV charging in the early afternoon. Controlled charging could further "smooth" the net demand profile and reduce peak capacity requirements created by PHEV demand.

The overall impact of PV and PHEVs on peak capacity requirements can be observed in Fig. 8, which plots the change in net peak demand as a function of PHEV penetration. Three levels of PV penetration are also shown – zero PV and PV meeting 5% and 10% of the system's annual energy demand. In each PV penetration, two charging scenarios are provided – unrestricted charging, and a case where charging is restricted after 3 pm. Depending on the scenario, adding PV reduces, or eliminates the increase in peak capacity requirements.

The second co-benefit of PV & PHEV deployment is to avoid curtailed energy during period of high PV and low normal demand. This is illustrated in Fig. 9. It shows the same scenario as Fig. 1, (April 25–28 where PV provides 15% of the system's annual demand), but a 30% PHEV penetration has been added with a corresponding charging profile. The overnight PHEV charging is controlled, but in this case the daytime charging pattern is uncontrolled to examine the inherent coincidence between PV supply and normal charging patterns. During the middle of each day the PV output is sufficient to reduce net load to very low levels, however uncontrolled PHEV charging is able to absorb some of the energy during periods of low demand.

While Fig. 9 shows that even uncontrolled charging will reduce potentially unusable PV, the timing of the charging is not optimal, because more charging occurs in the morning, when the PV output is low, than in the afternoon. This can also produces a 1-h spike in

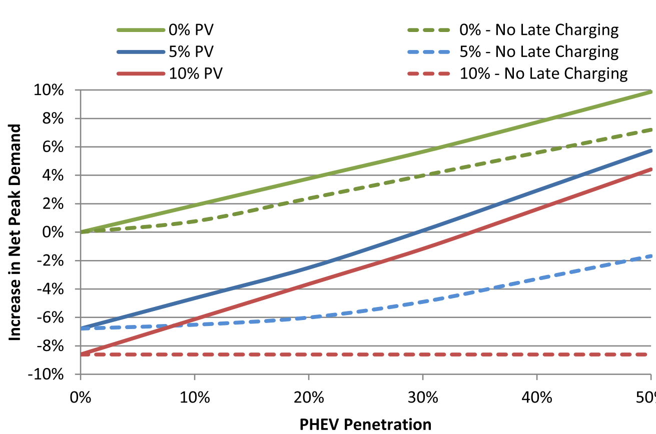

Fig. 8. Increase in peak capacity requirements as a function of PHEV-20 and PV penetration.

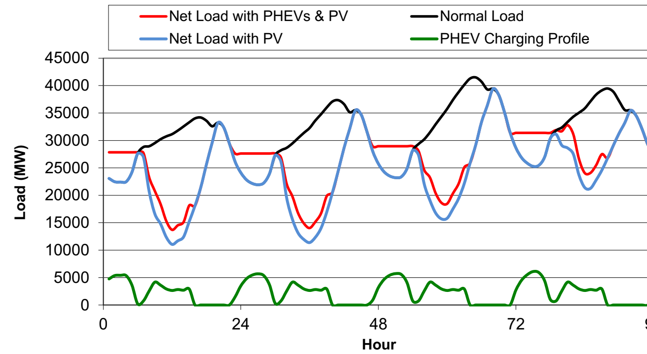

Fig. 9. Increased electric demand due to mid-day PHEV charging during April 25–28, with a PHEV-20 penetration of 30% where PV provides 15% of the system's annual electricity supply.

the morning demand due to charging that occurs before significant PV production occurs. By delaying some of the morning charging to the hour of peak demand, the net demand pattern with be smoother, and less curtailment may occur. Fig. 10 adds controlled charging to the morning period, assuming that this charging can be delayed by up to 2 h.

The availability of controllable mid-day charging increases the potential use of PV in at least two ways. The first is the ability to increase the coincidence of PHEV charging energy with PV supply, reducing potential curtailment. However the actual amount of curtailment will also be driven by the overall flexibility of the grid. The minimum generation point is partially driven by the need to keep partially loaded thermal generators online to provide a variety of operating reserves including contingency reserve and regulation reserve. Some of this reserve can potentially be provided by interruptible PHEV charging increasing grid flexibility.

It will be some time until large scale penetration of either PHEVs or PV is achieved, and since the grid will evolve, the exact flexibility of the future grid cannot be precisely quantified. However the general potential impact of PHEVs on PV curtailment can be illustrated. Fig. 11 demonstrates how mid-day PHEV charging can decrease PV curtailment. The scenarios consider a PHEV-20 penetration from 0% to 50%, and two PV penetration/system flexibility combinations. PV penetration is defined as the fraction of the base demand met by usable PV (without any PHEVs on the system). In each of the two PV scenarios, both uncontrolled and controlled daytime charging is also considered (where daytime charging can be delayed up to two hours). In all cases, there is decrease in the amount of curtailed PV generation as a function of PHEV penetration, with a greater decrease if daytime charging can be delayed to periods of greater solar output.

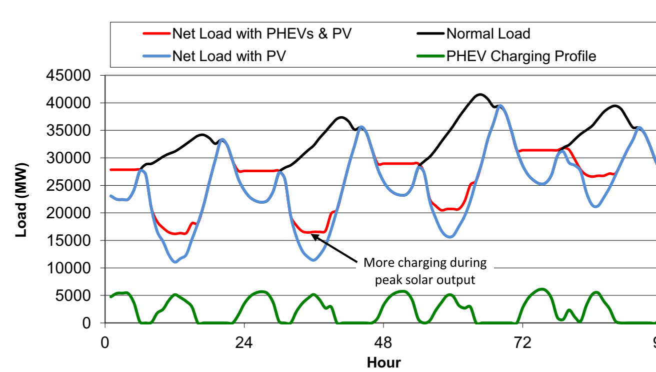

Fig. 10. Same scenario as Fig. 9, except mid-day charging is controlled with a delay of up to 2 h.

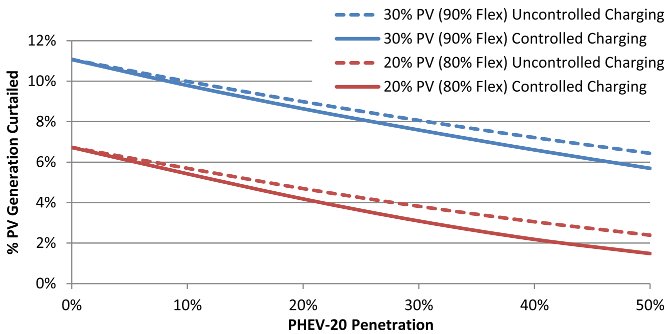

Fig. 11. Decrease in PV curtailment as a function of PHEV penetration.

Fig. 11 indicates that PHEVs can provide an important option for increasing the use of solar PV by providing a flexible source of electricity demand. However there are several other potential benefits of PHEVs to PV integration not considered in this analysis. Most notably, it does not consider the value of vehicle to grid (V2G) where the vehicles may discharge into the grid. V2G can provide operating reserves and improve overall grid flexibility by reducing the need to keep partially loaded thermal generators online [12,36,37]. However even without V2G, the ability to control charging could also provide operating reserves and provide system flexibility [38]. Additional analysis will be needed to examine the complete set of benefits PHEVs can provide in integrating PV and other variable generation sources. Finally, while this analysis focuses on co-benefits on the transmission system, additional analysis is needed to examine interactions on the distribution system. In particular, the ability to locate PV on the distribution system could help mitigate feeder-level challenges of mid-day charging in congested areas. In general, this analysis will need to be site-specific, building on methods and analysis previously performed [5,25,26].

6. Conclusions

Solar PV and PHEVs are two technologies that have significant potential for reducing carbon emissions and fossil fuel use. Each has barriers to very large scale deployment. For PV, its variable nature and the concentration of electricity output in the middle of the day limits its contribution to meeting a large fraction of normal electricity demand. For PHEVs, high cost batteries limit their economic potential.

When deployed together, these technologies can provide mutual benefits. Improved economic performance of PHEVs could be enabled by the availability of mid-day charging, increasing the distance traveled using low-cost electricity, and potentially reducing the size of the battery. However mid-day charging potentially increases peak generation requirements. PV provides a potential source of mid-day generation capacity for PHEVs, while PHEVs provide a dispatchable load for low value or otherwise unusable PV generation during periods of low demand (particularly in the spring). Depending on the penetration of each technology, PV could meet all of the increased capacity requirements associated with PHEV deployment, while PHEVs could absorb much, but not all of the potentially curtailed PV generation. This makes PHEVs and PVs potentially important complements to each other and additional enabling technologies such as load shifting and electricity storage.

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